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METHOD AND DEVICE FOR THE POSITIONALLY PRECISE MOUNTING OF AN
ADD-ON PART ON A VEHICLE BODY

[0001] The invention relates to a method for the mounting of an add-on part on a workpiece, in particular on a vehicle body, in which the add-on part is mounted on the workpiece in a precisely positioned manner in relation to a reference region, in accordance with the precharacterizing clause of patent claim 1, as disclosed, for example, in EP 470 939 A1. Furthermore, the invention relates to a mounting system for carrying out this method.

[0002] Over the course of the assembly process, add-on parts (for example, rear module, front module, roof module, cockpit, ...) are added on or installed in vehicle bodies, at different locations in the outer and inner regions. In the interests of obtaining a high-quality appearance of the body, it is necessary to align these add-on parts in a highly precise manner in relation to adjacent regions on the body or in relation to other (adjacent) add-on and installation parts, and to position them in such a manner that predetermined (gap) transition dimensions between the add-on part and the adjacent body regions are ensured. For this purpose, the add-on part has to be aligned in a precisely positioned manner in relation to the body and in this state has to be secured on the body with the aid of a joining method - for example by bolting on, spot-type welding or bonding.

[0003] For example, the front module has to be fitted into the (remaining) body in such a manner that gap dimensions and transitions which are as uniform as possible are achieved between the front module and the engine hood or between the front module and the wings. In order to ensure such a highly precise alignment of the front module in relation to the adjacent body regions, the front module has first of all to be aligned in a precisely positioned manner in relation to the adjacent regions of the body and then connected in this state to the body.

[0004] EP 470 939 A1 proposes a mounting method, with the aid of which a precisely positioned alignment and securing of an add-on part - in particular of a vehicle door - in a door cutout of a vehicle body is to be achieved. In this case, use is made of a robot-guided mounting tool which removes the add-on part from a workpiece carrier and inserts it into the

door opening. In this method, the mounting tool is first of all moved - without the add-on part - into a (spatially fixed) reference position in relation to the door opening; in this reference position, cameras which are connected fixedly to the mounting tool are used to take images of the region surrounding the door opening, these images being used to calculate the position of the door opening relative to the reference position of the mounting tool. The mounting tool then removes an add-on part from the workpiece carrier. The mounting tool - this time with the add-on part - is then moved again into the reference position; in this reference position, the cameras mounted on the mounting tool are used to take a further (second) set of images which are used to calculate the position of the add-on part held in the mounting tool. By means of a comparison of the two sets of image data, a movement vector is determined by which the mounting tool is displaced in order to compensate for an offset between the spatial positions of the door opening and of the add-on part and thereby thus to align the add-on part in relation to the door opening. In this corrected spatial position, the add-on part is connected to the body (using welding robots).

[0005] The method disclosed in EP 470 939 A1 is based on two sets of image data of the door opening and of the add-on part, which sets are both taken in a (spatially fixed) reference position of the mounting tool. The method is therefore based on the recording of the absolute positions of the body and of the add-on part relative to the reference position in the working area of the robot, on the arm of which the mounting tool is secured. For the successful use of this method a number of boundary conditions have to be satisfied:

- First of all, each camera used for determining the position has to be capable of determining individual measured values metrically with regard to its internal reference coordinate system ("internal metric calibration of the cameras").
- Furthermore, the position of the cameras in the working area of the robot has to be known ("external metric calibration of the cameras").
- Finally, the individual measurements of the cameras have to be combined and compressed in such a manner that the precise absolute position of the body opening or of the add-on part with regard to the working area of the robot can be calculated consistently and reliably.

In order to calibrate the sensors, EP 407 939 A1 provides a calibrating device (not described specifically) which has to be brought up in each cycle of the robot. Experience has shown that the outlay on setting up and calibrating the cameras and the overall system, which outlay

is required for satisfying the abovementioned boundary conditions, is very high, and this can only be carried out by experts. In addition, a high level of accuracy and ability to reproduce the measured values can be carried out only by means of high-quality (and therefore expensive) sensors.

[0006] A further problem of the method proposed in EP 470 939 A1 is that the obtaining of image data about the body opening, on the one hand, and about the add-on part, on the other hand, takes place in different, temporally offset process steps. Even slight movements of the body during the positioning operation therefore result in errors and have to be prevented.

[0007] The invention is therefore based on the object of proposing a method for the precisely positioned mounting of an add-on part on a workpiece, in particular on a vehicle body, which is associated with a substantially reduced outlay on calibration and which permits an increase in accuracy in comparison to known methods - even if cost-effective sensors are used. The invention is furthermore based on the object of proposing a mounting system suitable for carrying out the method.

[0008] According to the invention, the object is achieved by the features of claims 1 and 6.

[0009] In order to position and secure the add-on part on the body, use is made of a mounting tool, which is guided by means of a robot and comprises a fixing device for picking up the add-on part and a sensor system, which is connected fixedly to the mounting tool. The fixing device of the mounting tool is loaded with an add-on part and is first of all brought, under robot control, into a "proximity position" in relation to the body (which position has been permanently programmed in and is independent of the current position of the body in the working area of the robot). Starting from this proximity position, a closed-loop control process is run through, in the course of which the mounting tool is moved into a "mounting position", in which the add-on part held in the fixing device is aligned in a precisely positioned manner in the desired installation position in relation to the body. In the course of the closed-loop control process, (actual) measured values of selected reference regions are produced by the sensor system on the body and on the add-on part; these (actual) measured values are compared with (desired) measured values which have been produced in a preceding setting-up phase. The mounting tool is then displaced by a movement vector

(comprising linear movements and/or rotations) which is calculated from a difference between the (actual) and (desired) measured values using a “Jacobi matrix” (or “sensitivity matrix”). Both the (desired) measured values and the Jacobi matrix are determined within the context of a setting-up phase - which is arranged upstream of the actual positioning and mounting operation, within the context of which the mounting tool is taught the specific mounting task (i.e. a specific combination of mounting tool, sensor system, body type and manner and installation position of the add-on part to be inserted). This setting-up process is particularly advantageous, since it can be carried out solely by trained personnel “pointing” to a desired position.

[0010] If the above-described control operation is terminated and the add-on part held in the mounting tool is therefore in the desired mounting position in relation to the body, then the add-on part is mounted on the body in this position and alignment. In this connection, the add-on part is bolted to the body, for example with the aid of robot-guided screwdrivers and spanners. The fixing device of the mounting tool is then released, and the mounting tool is moved into a withdrawal position, in which the body is removed in a collision-free manner from the working region of the robot and a new body can be supplied.

[0011] The positioning operation, which is run through in a control loop and within the context of which the add-on part held in the mounting tool is brought from the proximity position (approached under the control of a robot) into the mounting position (aligned in a precisely positioned manner with respect to the body), differs fundamentally from the positioning operation disclosed in EP 470 939 A1: this is because, in the method of EP 470 939 A1, in the course of the positioning, first of all the absolute position of the body (or of the body opening) in the working area of the robot is determined, this position then forming the basis for the alignment of the loaded mounting tool. In contrast to this, the method according to the invention is based on relative measurements, within the context of which a position information item (deposited in the setting-up phase) - corresponding to a set of (desired) measured values of the sensor system - is recovered by the control operation.

[0012] This results in two substantial simplifications in comparison to the prior art:

- Firstly, an internal metric calibration of the sensors is no longer necessary, since the sensors which are used no longer “measure”, but rather merely react to a monotonous

incremental movement of the robot with a monotonous change of its sensor signal. This means, for example, that, if a television or CCD camera is used as the sensor, the lens distortions within the camera no longer have to be compensated for or that, if a triangulation sensor is used, the exact metric calculation of distance values is unnecessary.

- Furthermore, an external metric calibration of the sensors is no longer required: in contrast to the prior art, the position of the sensors no longer has to be determined metrically with regard to the working area of the robot or the coordinate system of the robot hand in order to be able to calculate suitable correction movements. The sensors have merely to be secured on the mounting tool in such a manner that they can record in their capture range any measured data which are at all suitable concerning the reference regions on the body and the add-on part.

[0013] When the method according to the invention is used, the metric measurement function, which as a rule can only be determined with a great outlay, and the calibrating device shown in EP 470 939 A1 can therefore be entirely omitted. Use can therefore be made of metrically uncalibrated sensors which are substantially more simple and therefore also cheaper than calibrated sensors. When the method according to the invention is used, both the instrumentation and the setting-up and operation of the overall system can therefore be realized very cost-effectively. Furthermore, when the method according to the invention is used, the initial setting-up and maintenance of the mounting system is drastically simplified and can also be undertaken by trained personnel.

[0014] The result of the positioning of the add-on part in relation to the body is furthermore independent of the absolute positioning accuracy of the robot used, since possible robot inaccuracies are sorted out as the mounting position is approached. Owing to the short error chains resulting therefrom, a very high repeating accuracy in the positioning result can be obtained, when required.

[0015] The number of degrees of positional freedom which can be compensated for in the positioning phase by the method according to the invention can be freely selected and depends only on the configuration of the sensor system. Similarly, the number of sensors used can be freely selected. The number of (scalar) sensor information items supplied has

merely to be equal to or greater than the number of degrees of freedom to be adjusted. In particular, a relatively large number of sensors can be provided, and the redundant sensor information can be used, for example, in order to be able better to record shape defects of the body region under consideration and/or with the add-on part to be fitted in or to improve the accuracy of the positioning operation. Finally, use can be made of sensor information from different, contactless and/or tactile sources (for example, a combination of CCD cameras, optical gap sensors and tactile distance sensors). Thus, by using suitable sensors, the measuring results of different variables relevant to quality (for example, gap dimensions, transition dimensions, depth dimensions) can be taken into consideration in the process of fitting in the add-on part. In the case of mounting tasks on vehicle bodies, use can be made, with particular advantage, of contactless sensors (for example gap sensors) which perform measurements in the UV spectral range, are distinguished by high insensitivity to various surface-area properties and are therefore particularly suitable for recording geometrical features on transparent surfaces and on painted or unpainted vehicle bodies. Sensors of this type and the principle of measurement on which they are based are described, for example, in German patent application 103 36 666.0.

[0016] The method according to the invention can very easily be adapted to new problems, since only the obtaining and preparation of sensor data, but not the controlling system core has to be adapted. The positioning operation can be carried out without using model knowledge about the body and the add-on part to be fitted in.

[0017] In comparison to the method of EP 470 939 A1, the invention permits a substantially more rapid compensation of residual uncertainties which may occur during the positioning of the add-on part in relation to the body opening; such residual uncertainties may come about because of errors in positioning the body in the working region of the robot due to delivery techniques, because of positional deviations of the add-on part in the mounting tool and/or due to shape defects of the add-on part to be fitted in or of the body, which defects are caused by component tolerances and tolerances in the modular construction. Furthermore, robot errors (for example, changes due to temperature fluctuations or differences) are compensated for.

[0018] Owing to this rapid adjustment of the position of the mounting tool in relation to the body, the body does not need to be clamped in a stationary manner during the positioning operation; on the contrary, it can be moved in relation to the robot (for example on an assembly line or other suitable conveying technique). This makes it possible for the method according to the invention to be highly flexible to therefore be able to be used in a very wide variety of application situations of mounting add-on parts on stationary and moving workpieces.

[0019] The controlled approach of the mounting position can take place in a single control loop; however, it is advantageous in this case for use to be made of an iterative method, in which threshold values are predetermined as termination criteria: thus, the iteration operation is terminated if the deviation between the taught (desired) measured value and the current (actual) measured value lies below a predetermined threshold value; furthermore, the iteration operation is terminated if the reduction of the deviation between the (desired) measured value and (actual) measured value that is to be achieved during consecutive iteration steps lies below a further predetermined threshold value.

[0020] The add-on part, which is aligned in the mounting position by means of the closed-loop control process, can - as described above - be connected directly to the body by bolting, spot welding etc. As an alternative, however, a joining method may be used, in which the add-on part, which is aligned in the mounting position, has to be briefly removed from the mounting position before the actual securing on the body in order, for example, to apply an adhesive bead to a connecting region in the body opening and/or of the add-on part. In this case, the mounting method advantageously comprises the following process steps:

- A the mounting tool is loaded with an add-on part to be installed and is moved - in accordance with the above-described, iterative control operation - from the proximity position (approached in a controlled manner) into the mounting position in relation to the body, in which position the add-on part is aligned in a precisely positioned manner in relation to the body opening;
- B the mounting tool is displaced under robot control from the mounting position by a fixedly predetermined offset into a yielding position in order to provide space in the mounting region for a robot-guided auxiliary tool, for example a bonding robot;

- C the auxiliary tool is moved into the mounting region where it works on the body opening and/or the add-on part (by applying an adhesive bead, for example, to the body opening) and is then moved out of the mounting region;
- D the mounting tool is displaced under robot control by the fixedly predetermined offset from the yielding position back into the mounting position (and the add-on part held in the mounting tool is therefore again positioned in a precisely positioned manner in the mounting region);
- E the add-on part is secured on the body region, if appropriate with the aid of a further auxiliary tool (or - in the case of an adhesive connection - is held in the mounting position until a first crosslinking of the adhesive has taken place);
- F the fixing device of the mounting tool is released, and the mounting tool is moved into the withdrawal position.

[0021] Process step B corresponds in this context to a “shifting away” of the add-on part which is reversed in process step D. The essential factor here is for the process steps B, D and E to be carried out under robot control as relative movements to the mounting position found in process step A, so that the mounting position found in the control operation of process step A can be used as the reference position for the further auxiliary tools involved in these process steps. In process step E of the mounting method, an additional sorting of the target position of the add-on part can advantageously take place in order to eliminate any inaccuracies of the process step.

[0022] Further advantageous refinements of the invention can be gathered from the subclaims. The invention is explained in greater detail below with reference to an exemplary embodiment which is illustrated in the drawings, in which:

[0023] Fig. 1 shows a schematic frontal view of a front region of a vehicle body;

[0024] Fig. 2 shows a schematic side view of a front opening of a vehicle body and of a robot-guided mounting tool with a front module;

[0025] Fig. 3 shows a schematic top view of the body and of the mounting tool of figure 2;

[0026] Fig. 4 shows a schematic illustration of the movement path of the mounting tool during the carrying out of the mounting of the front module of figures 1 to 3;

[0027] Fig. 5 shows a schematic sectional view of a roof region of a vehicle body during the mounting of the roof module ...

Fig. 5a ... with the roof module in the mounting position, and

Fig. 5b ... with the roof module in the yielding position.

[0028] Figure 1 shows a frontal view of a vehicle 8 with a front module 3 as an example of an add-on part which, within the context of the assembly of the vehicle, is bolted onto a workpiece, namely a body shell 1. Figure 2a shows in a side view the front region of this body shell 1 with a front opening 2 into which the front module 3 is installed. The body 1 comprises an engine hood 9 and wings 10 while a headlamp module 11 forms part of the front module 3.

[0029] In order to ensure a high-quality optical impression of the finished vehicle 8, the front module 3 has to be mounted on the engine hood 9 and the wings 10 in a precisely positioned manner (in respect of position and angular position) in relation to the regions 12, 13 adjacent to the front opening 2 of the body 1; in particular, a gap 15 (shown by dashed lines in figure 1) present between the front module 3, engine hood 9 and wings 10 has to have a predetermined size corresponding to certain requirements. In this case, the surrounding regions 12, 13, 9 form a “reference region” for the alignment of the front module 3 in relation to the body 1.

[0030] The mounting of the front module 3 into the body 1 takes place with the aid of a mounting tool 5 which is guided by an industrial robot 14 and supplies the front module 3 and positions it in a precisely positioned manner in relation to the front opening 2 of the body 1. A open-loop control system 16 is provided for controlling the position and movement of the robot 14 and of the mounting tool 5.

[0031] The mounting tool 5 is secured on the hand 17 of the industrial robot 14 and comprises a frame 18 on which is secured a fixing device 19, with the aid of which the front module 3 can be picked up. The fixing device 19 is advantageously arranged in a manner

such that it can rotate and/or pivot in relation to the frame 18 of the mounting tool 5, so that, after the mounting is finished, it can easily release the front module 3 and can be removed from the mounting region.

[0032] To measure the position and alignment of the front module 3, which is fixed in the mounting tool 5, in relation to the body 1, the mounting tool 5 is provided with a sensor system 20 having a plurality of sensors 21 (two in the schematic illustration of figure 2) which are connected rigidly to the frame 18 of the mounting tool 5; they therefore form a constructional unit with the mounting tool 5. These sensors 21 are used for determining gap and/or transition dimensions between edge regions 22 of the front module 3 and the adjacent regions 12, 13 on the engine hood 9 and wings 10 of the body 1. With the aid of this sensor system 20 - as described further below - the front module 3 which is held in the mounting tool 5 is aligned in relation to the front opening 2 of the body 1 in an iterative control operation.

[0033] If the mounting system 5 is to be set to a new working task - for example to the mounting of the front module in a new type of vehicle - then first of all a "setting-up phase" has to be run through, in which the mounting tool 5 is configured. In this case, a fixing device 19 which is adapted to the front module 3 to be mounted, a suitably designed frame 18 and a sensor system 20 with corresponding sensors 21 is selected and assembled. Following this, the sensor system 20 of the mounting tool 5 is "taught" by - as described below under I. - (desired) measured values of the sensor system 20 being picked up on a "master" body 1' and a "master" front module 3' and those path sections of a movement path 23 of the robot 14 that are to be run through under open-loop control being programmed in. After this setting-up phase is ended, the thus configured and calibrated mounting system 4 is now ready for series use, in which for each body 1 supplied to a working area 24 of the robot 14 a "working phase" is run through, in which - as described below under II. - an associated front module 3 is positioned and secured in the front opening 2 of the body 1.

[0034] I. Setting-up phase of the mounting tool 5:

[0035] In order to resolve a newly set mounting task, in a first step first of all a sensor system 20 which is adapted to the mounting task is selected for the mounting tool 5 and is secured

together with the fixing device 19 on the frame 18. The thus assembled mounting tool 5 is secured on the robot hand 17. The fixing device 19 is then loaded with a (“master”) front module 3’ and aligned (manually or interactively) in such a manner in relation to a (“master”) body 1’ in the working area 24 of the robot 14 that an “optimum” alignment of the (“master”) front module 3’ in relation to the (“master”) body 1’ is provided; this relative position of the (“master”) front module 3’ in relation to the (“master”) body 1’ is illustrated in figure 2b. An “optimum” alignment of this type can be defined, for example, by the gap 15 between the (“master”) front module 3’ and the (“master”) body 1’ being as uniform as possible (see figure 1), or by the gap 15 taking up certain values in certain regions. The relative position taken up in the process of the mounting tool 5 in relation to the (“master”) body 1’ is referred to below as the “mounting position” 25.

[0036] The number and the position of the sensors 21 on the frame 18 are selected in such a manner that the sensors 21 are directed at suitable regions 12, 13 on the (“master”) body 1’ or at regions 22 of the (“master”) front module 3’, which regions are particularly important for the “optimum” alignment. In the exemplary embodiment of figure 2a, two sensors 21 are shown symbolically, of which one is directed at the gap 15 between the upper edge region 26 of the headlamp module 11 and that region 12 of the engine hood 9 which is adjacent to it in the assembled position, while the other carries out a gap measurement between the side region 27 of the front module 3 and the front region 13 of the wing 10 (or between the headlamp 28 and wings 10). The number of individual sensors 21 and the surroundings 12, 13, 26, 27 at which they are directed are selected in such a manner that they permit the best possible characterization of the quality features relevant for the particular application. In addition to the gap measurement sensors, further sensors may be provided which measure, for example, a (depth) distance between the body 1 and front module 3. In order, on the one hand, to obtain the greatest possible insensitivity to paint effects of the body 1 and, on the other hand, to achieve measuring results which can be used even on the (transparent) plastic coverings 28 of the headlamp modules 11, use is advantageously made of optical sensors in the UV spectral range.

[0037] The mounting tool 5 with the sensor system 20 and with the (“master”) front module 3’ held in the fixing device 19 is now “taught” with the aid of the robot 14 to the mounting position 25 (which is set by the manual or interactive alignment and is taken up in the

illustration of figure 2b) in relation to the (“master”) body 1’. In this case, first of all measured values of all of the sensors 21 in the mounting position 25 are picked up and are stored as “desired measured values” in an evaluation unit 29 of the sensor system 20; this sensor evaluation unit 29 is expediently integrated in the open-loop control system 16 of the robot 14. Then - starting from the mounting position 25 - the robot 14 is used to systematically change the position of the mounting tool 5 and the (“master”) front module 3’ held in it in relation to the (“master”) body 1’ along known movement paths - as indicated by arrows 30 in figure 2b; these are generally incremental movements of the robot 14 within its degrees of freedom. The changes occurring in the process of the measured values of the sensors 21 are recorded (entirely or in parts). A “Jacobi matrix” (sensitivity matrix) is calculated - in a known manner - from these sensor information items, the Jacobi matrix describing the relationship between the incremental movements of the robot 14 and the changes occurring in the process of the measured values of the sensors. The method for determining the Jacobi matrix is described, for example, in “A tutorial on visual servo control” by S. Hutchinson, G. Hager and P. Corke, IEEE Transactions on Robotics and Automation 12(5), October 1996, pages 651-670. This article also describes the requirements imposed on the movement travel and the measuring surroundings (continuity, monotony, ...) which have to be satisfied in order to obtain a valid Jacobi matrix. - The incremental movements are selected in such a manner that collisions of the mounting tool 5 or of the (“master”) front module 3’ with the (“master”) body 1’ cannot occur during this setting-up operation.

[0038] The Jacobi matrix produced in the setting-up phase is stored together with the “desired measured values” in the evaluation unit 29 of the sensor system 20; these data form the basis for the subsequent positioning control operation A-2 in the working phase (see below under II.).

[0039] Furthermore, a movement path 23 of the robot hand 17 (and therefore of the mounting tool 5) is generated in the setting-up phase and is run through under open-loop control in the later working phase II. This movement path 23 is illustrated schematically in figure 4. The starting point of the movement path 23 is formed by a “withdrawal position” 31 which is selected in such a manner that a new body 1 can be introduced into the working area 24 of the robot 14 without any fear of collisions of the body 1 with the mounting tool 5 or the front

module 3 held therein. This withdrawal position 31 can correspond, for example, to a removal station 32, in which the mounting tool 5 removes a front module 3 which is to be used from a workpiece carrier 33 or from a belt conveyor (see figure 3). Starting from this withdrawal position 31, the movement path 23 comprises the following separate sections:

- A-1 The mounting tool 5 with front module 3 inserted is brought on a path A-1, which is to be run through under open-loop control, from the withdrawal position 31 into a fixedly predetermined "proximity position" 34 which is selected in such a manner that all of the individual sensors 21 of the sensor system 20 can record valid measured values of the particular region 12, 13, 26, 27, 9, 28 of the front module 3 and/or of the body 1 while it is ensured at the same time that collisions of the mounting tool 5 or of the front module 3 with the body 1 cannot occur.
- A-2 The mounting tool 5 with front module 3 inserted is brought on a path A-2, which is to be run through under closed-loop control, from the proximity position 34 into the "taught" (as described above) mounting position 25, in which the front module 3 held in the mounting tool 5 is aligned in a precisely positioned and angularly precise manner in relation to the front opening 2 of the body 1. The details of what takes place during this process step which is to be run through under closed-loop control are described further below (in the II. Working phase).
- F The fixing device 19 is released, and the mounting tool 5 is moved back under robot control into the withdrawal position 31.

[0040] The movement path 23 of the mounting tool 5, which path is produced within the context of the setting-up phase, therefore comprises two sections A-1 and F, which are passed through under open-loop control in the later working phase, and one section A-2 which is to be passed through under closed-loop control in the later working phase. The steps A-1 and F may be input interactively during the teaching phase of the mounting tool 5, or they may be stored in the form of a program (if appropriate generated off-line) in the open-loop control system 16 of the robot 14.

[0041] II. Working phase

[0042] In the working phase, bodies 1 are supplied sequentially (for example on a conveyor belt) into the working area 24 of the mounting system 4, are lifted out of the conveying

technique there for the duration of the mounting operation, and with the aid of the mounting system 4 - using the movement path taught in the setting-up phase - are provided with front modules 3 mounted in a precisely positioned manner (see figure 3).

[0043] Movement-path section A-1 (proximity phase):

[0044] During the supply of the new body 1, the mounting tool 5 is in the withdrawal position 31 where it picks up from the removal station 32 a front module 3 which is to be mounted; this is illustrated in figure 3 by dashed lines. The picking up of the front module 3 can take place, as described for example, in (PCT patent application ..., our file P803860/WO/1), by means of a controlled process with the aid of a measuring sensor arrangement, so that a defined position of the front module 3 in the fixing device 19 is ensured. Then, when picking up the front module 3 from the workpiece carrier 33, use is advantageously made of the sensor system 20 of the mounting tool 5, which sensor system is directed at the regions 26, 27, 28 of the front module 3 and therefore supplies suitable measured values for a controlled positioning operation of the mounting tool 5 in relation to the front module 3. - However, the front module 3 may just as well be picked up "imprecisely" in the fixing device 19 because - as depicted below during the description of the movement-path section A-2 - any inaccuracies of the front module 3 with respect to its position in the fixing device 19 are sorted out during the alignment of the front module 3 in relation to the body 1.

[0045] As soon as the new body 1 has been moved into the working area 24 and fixed there, the mounting tool 5 with the front module 3 inserted (in a precisely positioned or imprecise manner) is moved in a controlled manner into the proximity position 34 of figure 2a.

[0046] Movement-path section A-2 (positioning phase of the mounting tool 5):

[0047] Starting from the proximity position 34, a positioning phase (path section A-2 in figure 4) of the mounting tool 5 is run through, within the context of which the front module 3, which is held in the mounting tool 5, is brought into the mounting position 25 (taught during the teaching phase) in relation to the body 1 and in the process is aligned in a precisely positioned manner in relation to the front opening 2 of the body 1. For this purpose, the

sensors 21 of the sensor system 20 are used to pick up measured values in selected regions 12, 13, 26, 27, 9, 28 of the front module 3 and of the body 1. These measured values and the Jacobi matrix determined in the setting-up phase are used to calculate a movement increment (movement vector) which reduces the difference between the current (actual) measured values of the sensors and the (desired) measured values of the sensors. The front module 3 held in the mounting tool 5 is then displaced and/or pivoted with the aid of the robot 14 by this movement increment, and new (actual) measured values of the sensors are picked up during the continuing movement.

[0048] This iterative measurement and movement operation is repeated in a control loop until the difference between the current (actual) and the sought (desired) measured values of the sensors falls below a predetermined error dimension, or until this difference no longer changes beyond a threshold value fixed in the preliminary stage. The front module 3 is now located (within the context of the accuracy predetermined by the error dimension or threshold value) in the mounting position 25 (illustrated in figure 2b) in relation to the body 1.

[0049] By means of the iterative minimization run through in this positioning phase A-2, inaccuracies of the body 1 with respect to its position and alignment in the working area 24 of the robot 14 and also any existing shape defects of the front region 2 of the body 1 (i.e. deviations from the ("master") body 1') are compensated for. Simultaneously, inaccuracies of the front module 3 with respect to its position and alignment in the mounting tool 5 and any existing shape defects of the front module 3 (i.e. deviations from the ("master") front module 3') are compensated for. Thus, within the course of this iterative closed-loop control process, the front module 3 - irrespective of shape and positional inaccuracies - is fitted in the "optimum" manner into the front opening 2 of the body 1. For the separate recognition and assessment of shape defects of the front module 3 and of the body 1 additional sensors (i.e. not required for the actual positioning task) may be provided on the mounting tool 5, the measured values of which are used exclusively or partially for recording the shape defects. Furthermore, the measured values of the individual sensors 21 may be provided with different weighting factors in order to bring about a weighted positional optimization of the front module 3 in relation to the front opening 2 of the body 1.

[0050] An important characteristic of the positioning phase A-2 is its independence from the accuracy of the robot: since the positioning operation is based on an iterative comparison of the (actual) measured values with (desired) measured values, each position inaccuracy of the robot 14 is immediately compensated for by the iterative closed-loop control process.

[0051] Working step E (securing of the front module 3 on the body 1)

[0052] In the mounting position 25 of the mounting tool 5 that has now been taken up and in which the front module 3 is optimally positioned in relation to the front opening 2, the securing of the front module 3 on the body 1 takes place. For this purpose, use is made, for example, of separate robots 35 (indicated in figure 3) on which screwdrivers and spanners are secured.

[0053] Movement-path section F (withdrawal of the mounting tool 5):

[0054] After the front module 3 has been mounted, the fixing device 19 of the mounting tool 5 is released, so that the front module 3 is suspended freely on the body 1. In this position, it is possible, if appropriate, for measurements monitoring the joint dimensions, gaps and depth dimensions in the regions 12, 13, 26, 27, 9, 28 to be carried out (with the aid of the sensors 21); in the process, deviations from the desired dimensions are to be established, so that defined information about refinishing is sent to the operator of the system.

[0055] The fixing device 19 of the mounting tool 5 is then moved out of the engagement position in such a manner that the mounting tool 5 can be moved back in a collision-free manner and under robot control out of the mounting position 25 into the withdrawal position 31. The body 1 is unclamped, lifted out and conveyed. In parallel to this or subsequently, the mounting tool 5 is loaded with a new front module 3, and a new body 1 is supplied to the working area 24 of the mounting system 4.

[0056] Up to now it has been assumed that the front module 3 may have tolerances due to the manufacturing and/or may be picked up in a positionally imprecise manner in the mounting tool 5, for which purpose, for the fitting in of the front module 1, use has been made within the context of the positioning phase A-2 of measured values both of the edge regions 22, 26,

27 (relevant for the quality of fitting) of the front module 3 and of the adjacent regions 12, 13 of the body 1. - Another fitting strategy is possible, if the position of the front module 3 in the fixing tool 19 is known with a high degree of reproducibility, and if the front module 3 is tolerance-free (or may be assumed as being tolerance-free). In this case, in which a highly precise alignment of the front module in the mounting tool 5 is provided, measured values no longer have to be picked up for the edge regions 22, 26, 27 of the front module 3 within the context of the positioning phase A-2 in order to fit the front module 3; in this case, it suffices to carry out the closed-loop control process during the positioning phase using measured values of sensors which are directed at the adjacent regions 12, 13, 9 of the body 1.

[0057] For data communication between the different system components (evaluation unit 29 of the sensor system 20 and the control unit 16 of the robot 14), in the present exemplary embodiments use is advantageously made of a TCP/IP interface which makes a high data rate possible. Such a high data rate is necessary in order to be able, during the positioning phase A-2 which is to be run through under closed-loop control, to manage with an adjustment of the entire system (sensor systems/robots) with the multiplicity of individual sensors 21 within the interpolation cycle of the robot 14 (typically 12 milliseconds). For adjustment problems of less complexity - i.e. when lower requirements are imposed on the accuracy and when there are longer control times - the adjustment may also be realized via a conventional serial interface.

[0058] In working phase II., it is to be ensured during the positioning phase A-2 that no touching contacts occur between the front module 3 and the body 1; such touching contacts are namely associated with frictional forces which may considerably impair the positional adjustment of the front module. Interfering touching contacts of this type may occur, for example, if the body 1 has been positioned too imprecisely in the working area 24 of the robot 14 or if the longitudinal member consoles have excessively large tolerances.

[0059] In the present exemplary embodiment, during the control phase, in particular, touching contacts have to be avoided with the longitudinal member consoles (not depicted in the figures) of the body 1, to which the front module 3 is bolted in the working step E and which are aligned perpendicularly with respect to the longitudinal direction of the vehicle. - In order to avoid these touching contacts, the proximity phase A-1 is advantageously

designed in such a manner (or the proximity position 34 is approached in such a manner) that, during the successive positioning phase A-2, it is not possible for the front module 3 to come into contact with the longitudinal member consoles:

- For example, the sensor system 20 can be provided with additional (distance) sensors (not shown in the figures) which measure the distance of the front module 3 from the longitudinal member consoles. The approach of the proximity position 34 takes place under closed-loop control, with the measured values of the distance sensors as controlled variable; the proximity position 34 is reached when the distance in the longitudinal direction of the vehicle between the front module 3 and the longitudinal member consoles has a predetermined size (for example, 2 mm). Starting from this proximity position 34, in the positioning phase A-2 which then follows, using the gap sensors 21, the front module 3 is displaced and rotated in a plane perpendicular with respect to the longitudinal direction of the vehicle until the optimum dimensions for the gap 15 are reached.
- As an alternative, within the context of the proximity phase A-1, the front module 3 can first of all be brought actively into touching contact with the longitudinal member consoles, this contact situation being detected with the aid of force/moment sensors which are installed, for example, between mounting tool 5 and robot hand 17. Starting from this contact situation, the front module 3 is then lifted off from the longitudinal member consoles by a certain distance (for example, 2 mm). This position defines the proximity position 34 and forms the starting point for the positioning phase A-2, during which the front module 3 is aligned in the remaining degrees of freedom in relation to the surrounding body regions 12, 13.
- As an alternative, the mounting tool 5 can be mounted during the proximity phase A-1 on the robot hand 17 in a floating manner. The mounting tool 5 which is mounted in a floating manner is brought with the front module 3 held in it up to the body 1 until the front module 3 is in touching contact with all of the longitudinal member consoles; in this alignment, the angular position of the mounting tool 5 in relation to the robot hand 17 is fixed by the floating mounting being clamped. The mounting tool 5 is then removed by the robot 14 from the body 1 in a defined manner by a certain amount (for example, 2 mm) in the longitudinal direction of the vehicle, so that the contact situation between the front module 3 and longitudinal member consoles is eliminated.

This defines the proximity position 34 and forms the starting point for the positioning phase A-2 which then follows.

Generally speaking, the touching contacts are suppressed in the positioning phase A-2 by, during the proximity phase A-1, the position of the front module 3 in relation to the body 1 being positioned and fixed in a number of degrees of freedom (here: in the longitudinal direction of the vehicle) while, in the positioning phase A-2, only an optimization of the position of the front module in the remaining degrees of freedom (here: perpendicular with respect to the longitudinal direction of the vehicle) takes place. After the end of the positioning phase A-2, the contact situation between the front module 3 and body 1 is reproduced at the beginning of the working step E, so that the front module 3 can be bolted to the longitudinal member consoles.

[0060] Figures 5a and 5b show, as a further application of the mounting method according to the invention, a schematic illustration of the mounting of a roof module 3'' in a roof opening 2'' of a body 1'', the intention being for the roof module 3'' to be bonded into the roof opening 2''. The reference numerals of the components involved in figures 5a and 5b correspond to the reference numerals of the exemplary embodiment of figures 1 to 3, but to differentiate them each is identified with a double prime (''). The roof module 3'' is supplied to the body 1'' in a robot-controlled mounting tool 5'' which is provided with a sensor system 20''. In this case, the sensors 21'' are preferably gap sensors which measure the width and depth of a gap 15'' between the roof module 3'' and surrounding roof frame 9'', 10''. They are directed at those reference regions 12'', 13'', 22'' on the roof module 3'' and roof frame 9'', 10'' which are of particularly great importance for the alignment of the roof module 3'' in relation to the roof frame 9'', 10''. The fixing device 19'' is formed in this case by negative-pressure suction cups which engage on the upper side 36 of the roof module 3''.

[0061] The teaching phase I of the mounting system 4'' takes place analogously to the above-described teaching phase of the front-module mounting system 4. Since, however, the roof module 3'' is to be connected to the body 1'' with the aid of a bonding process, an adhesive bead 38 has to be applied to a joining region 37 of the roof module 3'' and of the roof opening 2'' before the roof module 3'' is finally connected to the body 1''. The movement path 23'' must therefore contain the following, additional method steps which have to be run through between the positioning phase A-2 (to be run through under closed-loop control) and

the actual mounting (i.e. the final connecting of the roof module 3'' to the vehicle body 1'') (see the movement-path sections B, D shown by dashed lines in figure 4):

[0062] Movement-path section B (yielding phase of the mounting tool 5''):

[0063] Starting from the mounting position 25'', which has been approached under closed-loop control in the movement-path section A-2 and is illustrated in figure 5a, the mounting tool 5'' with the roof module 3'' held in it is transported by the robot 14'' under open-loop control into a yielding position 39 which lies outside a mounting region 40 positioned in the roof region of the body 1'' (see figure 5b). Before the actual approach of the yielding position 39, the positional and angular movement, which has taken place within the context of the control operation of the positioning phase A-2, of the roof module 3'' held in the mounting tool 5'' (corresponding to the movement between the proximity position 34'' and the mounting position 25'') can be passed on in the form of a "zero offset compensation" to the open-loop control system of the robot 14''. The open-loop control system of the robot 14'' therefore "recognizes" the starting position (corresponding to the mounting position 25''), which corresponds to the optimum fitting of the roof module 3'' into the roof opening 2'', and can pass on this starting position to further tools involved in the mounting, for example to a bonding robot 41.

[0064] By means of the movement of the roof module 3'' away under open-loop control into the yielding position 39, space is created in the mounting region 40 of the roof opening 2'' for a robot-guided bonding tool 42 which applies an adhesive bead 38 in the joining region 37 on the roof opening 2'' and subsequently withdraws again from the mounting region 40 (process step C). As a result, the area of the roof opening 2'' again becomes free for the mounting tool 5''.

[0065] Movement-path section D (return movement of the mounting tool 5''):

[0066] The mounting tool 5'' with the roof module 3'' is then moved back under robot control from the yielding position 39 into the mounting position 25'', as a result of which the roof module 3'' again comes to lie in a positionally and angularly precise manner in relation to the roof opening 2'' of the body 1'' and is connected in this state to the roof opening 2'' by

means of the adhesive bead 38. This path D can be, in particular, the “reverse” of the path B. The roof module 3'' is therefore bonded in the desired position and alignment to the roof opening 2'' of the body 1''.

[0067] The working step E, which corresponded in the preceding exemplary embodiment to the (mechanical) mounting of the front module 3 on the body 1, is omitted in this case. Analogously to the mounting of the front module, in the following path section F the fixing device (suction cups 19'') of the mounting tool 5'' is then released and the roof module 3'' therefore released; subsequently, the mounting tool 5'' is moved back into the withdrawal position 31'', the body 1'' is removed from the working region of the robot 14'' and a new body to be worked on is supplied.

[0068] In addition to the mounting of a front module and roof module in vehicle bodies - the method can be transferred to any desired other mounting circumstances, in which an add-on part 3, 3'' is to be mounted in a precisely positioned manner on a workpiece 1, 1'', in particular a body, with the aid of a robot-guided mounting tool 4, 4''. In the context of the present application, “robot-guided” tools are to be understood quite generally as meaning tools which are mounted on a multiaxial manipulator, in particular a six-axis industrial robot 14, 14''.